

## Magnetic cycles of Sun-like stars with different levels of coronal and chromospheric activity – comparison with the Sun

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**Abstract** The atmospheric activity of the Sun and Sun-like stars is analyzed involving observations from HK-project at the Mount Wilson Observatory, the California and Carnegie Planet Search Program at the Keck and Lick Observatories and the Magellan Planet Search Program at the Las Campanas Observatory. We show that for stars of F, G and K spectral classes, the cyclic activity, similar to the 11-yr solar cycles, is different: it becomes more prominent in K-stars. Comparative study of Sun-like stars with different levels of the chromospheric and coronal activity confirms that the Sun belongs to stars with the low level of the chromospheric activity and stands apart among these stars by the minimum level of its coronal radiation and the minimum level of its variations of the photospheric flux.

**Key words:** The Sun: activity, Sun-like stars: activity.

### 1 INTRODUCTION

The study of the magnetic activity of the Sun and Sun-like stars is of fundamental importance for astrophysics. This activity of stars leads to the complex of composite electromagnetic and hydrodynamic processes in their atmospheres. Local active regions, which are characterized by a higher value of intensity of the local magnetic field, are: plagues and spots in photospheres, CaII flocculae in chromospheres and prominences in coronas.

More powerful coronas are possessed by stars displaying irregular variations of their chromospheric emission, while stars with cyclic activity are characterized by comparatively modest X-ray luminosities and ratios of the X-ray to bolometric luminosity  $L_X/L_{Bol}$ . This indicates that the nature of processes associated with the magnetic-field amplification in the convective envelope changes appreciably in the transition from small to large dynamo numbers, directly affecting the character of the  $(\alpha - \Omega)$  dynamo. Due to the strong dependence of both the dynamo number and the Rossby number on the speed of axial rotation, earlier correlations were found between various activity parameters and the Rossby number in Bruevich et al. (2001).

It is difficult to predict the evolution of each active region in details. However, it has long been established that the total change of active areas integrated over the entire solar or stellar disk is cyclical not only in solar activity but in stellar activity too (see Baliunas et al. 1995; Kollath & Olah 2009; Morgenthaler et al. 2011; Bruevich & Kononovich 2011).

It is well known that the duration of the 11-yr cycle of solar activity (Schwabe cycle) ranges from 7 to 17 years according to a century and a half of direct solar observations.

The most sensitive indicator of the chromospheric activity (CA) is the Mount Wilson  $S$  - index ( $S_{HK}$ ) - the ratio of the core of the CaII H&K lines to the nearby continuum (Vaughan & Preston 1980). Now the CaII H&K emission was established as the main indicator of CA in lower main sequence stars.

The HK-project of Mount Wilson observatory is one of the first and still the most outstanding program of observations of Sun-like stars (see Baliunas et al. 1995; Lockwood et al. 2007). One of the most important results of the HK-project was the discovery of "11-yr" cycles of activity in Sun-like stars. Durations of CA cycles, found for 50 different stars of late spectral classes (F, G and K), vary from 7 to 20 years according to HK-project observations.

Currently, there are several databases that include thousands of stars with measured fluxes in the chromospheric lines of CaII H&K emission cores (see Wright et al. 2004; Isaacson & Fisher 2010; Arriagada 2011; Garcia et al. 2010; Garcia et al. 2014). However, only for a few tens of stars the periods of magnetic activity cycles are known (Baliunas et al. 1995; Radick et al. 1998; Lockwood et al. 2007; Olah et al. 2009; Morgenthaler et al. 2011).

In our work, we consider the following databases of observations of Sun-like stars with known values of  $S_{HK}$ :

1. HK-project – the program in which the Mount Wilson  $S$  value was first defined. Later the Mount Wilson " $S$  value" ( $S_{HK}$ ) became the standard metric of CA – the basic value with which all future projects of stellar CA observations are compared and calibrated.

2. The California & Carnegie Planet Search Program which includes observations of approximately 1000 stars at Keck & Lick observatories in chromospheric CaII H&K emission cores.  $S_{HK}$  indexes of these stars are converted to the Mount Wilson system (Wright et al. 2004). From these measurements, median activity levels, stellar ages, and rotation periods from general parameterizations have been calculated for 1228 stars,  $\sim 1000$  of which have no previously published  $S$ -values.

3. The Magellan Planet Search Program which includes Las Campanas Observatory CA measurements of 670 F, G, K and M main sequence stars of the Southern Hemisphere.  $S_{HK}$ -indexes of these stars are also converted to the Mount Wilson system (Arriagada 2011).

We believe that the stars in these databases are best described the stars which are similar to the Sun in mass and evolutionary state. They are main-sequence stars with a  $(B - V)$  color between 0.48 and 1.00 (the Sun has a  $(B - V)$  color of 0.66). Alternatively, a definition based on spectral type can be used, such as F5V through K5V.

The aims of our paper are: 1) a study of the place of the Sun among stars with different levels of chromospheric and coronal activity belonging to the main sequence on the Hertzsprung-Russell diagram; 2) a comparative analysis of chromospheric, coronal and cyclic activity of the Sun and Sun-like stars of F, G and K spectral classes.

## 2 THE PLACE OF THE SUN AMONG THE SUN-LIKE STARS WITH DIFFERENT LEVELS OF CHROMOSPHERIC AND CORONAL ACTIVITY

In Figure 1, the Sun and stars from different observed samples are presented on the Color-Magnitude Hertzsprung-Russell diagram. There are 1000 Sun-like stars from Wright et al. (2004), observed in the Program of Planet Search (open circles); 660 Sun-like stars from Arriagada (2011) observed in the Magellan Planet Search Program (asterisks) and 110 Sun-like stars and the Sun from Baliunas et al. (1995), observed in the Mount Wilson HK-project (filled circles). The solid line represents the Zero Age Main Sequence (ZAMS) on the Hertzsprung-Russell diagram.

Stars, which are close to the ZAMS in Figure 1, have the lowest age among all other stars:  $\log(\text{Age/yr})$  is about 8 - 8.5. The older the star is, the farther it is from the ZAMS. Ages of all the stars in Figure 1 varies from  $10^8$  to  $10^{10}$  years.

We can also see that some stars significantly differ from the Sun by the absolute magnitude  $M_V$  and color indices  $(B - V)$ .

In different samples of stars from Planet Search Programs, some observers included a number of subgiants with larger values of magnitudes  $M_V$  among Sun-like stars belonging to the main sequence. We try to exclude them from our analysis.

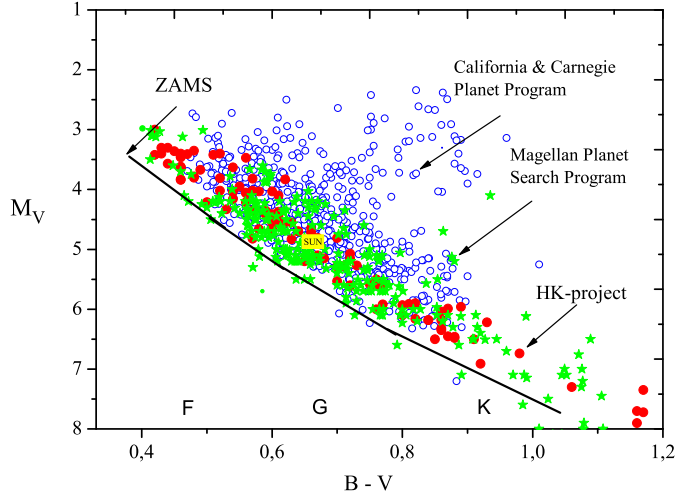


Fig. 1. The Sun among the Sun-like stars from different observational Programs on the Hertzsprung-Russell diagram.

In Figure 2, one can see that stars have significantly different values of the  $S_{HK}$ -index, which determines their CA. There are stars from the Program of Planet Search (open circles), the Magellan Planet Search Program (asterisks) and 110 stars and the Sun from the HK-project (filled circles).

We cannot see the close relationship of CA of stars from our samples versus the color index in Figure 2.

Figures 1,2 show that the more sun-like stars in pattern, the greater the spread in their luminosities  $M_V$  and chromospheric activity CA versus the Sun value.

It is important to note that the study of CA of stars are performed for very large data sets. Zhao et al. 2015 have studied a sample of  $\sim 120\,000$  F, G and K stars from the LAMOST DR1 archive, which is an unprecedentedly large sample for a study of the H&K CaII emission. The  $\delta S$  index was measured for these stars, calculated as the difference between standard  $S$ -index and a 'zero' emission line fitted using several of the least active stars across the whole range of  $T_{eff}$ . It was shown that active stars lie closer to the Galactic plane but inactive stars tend to be farther away from the Galactic plane.

For another large statistical sample – 2600 stars of the California Planet Search Program – the lower envelope of CA level  $S_{BL}$  ( $S_{HK}$  of the Basic Level) was defined as a function (polynomial fit) of  $B - V$  for main sequence stars over the color range  $0.4 < B - V < 1.6$ , see Isaacson et al. (2010).

We show the  $S_{BL}$  dependence in Figure 2. It is seen that the Basic CA Level  $S_{BL}$  begins to rise when  $B - V > 1$ . Isaacson et al. (2010) believed that this increase of  $S_{BL}$  is due to decrease of continuum flux for redder stars:  $S_{HK}$  is defined as the ratio of H&K CaII emission to the nearby continuum.

According to Isaacson et al. (2010), mean levels of CA (corresponding to the uniform Mount Wilson  $S$ -index) for stars of the spectral class F are higher than that of the G-stars. On the other hand, for stars of K and M spectral classes, mean levels of CA are also higher than that of G-stars. However it can be noted that the level of CA of the Sun is slightly below than the average level of CA of stars belonging to the main sequence.

The  $S_{HK}$  is affected by line blanketing in the continuum regions that increases with (B-V) color index. This effect gives mistakes in the comparison of CaII activity for stars of different color.

For describing the CA, it will be more correct to use the index  $\log R'_{HK}$ . The parameter  $\log R'_{HK}$  is calculated from the mean  $S_{HK}$  and the (B-V) color. It was originally formulated by Noyes et al. (1984). The HK-project stars sample ranges from  $\log R'_{HK} = -4.4$  (young stars) to  $-5.3$  (old stars). The solar value of  $\log R'_{HK} = -4.94$ .

In our paper we use  $S_{HK}$  when we study the observed time series ("light curves" of the H&K CaII emission) but below in this paper we will use  $\log R'_{HK}$  as the more correct index of the the CA.

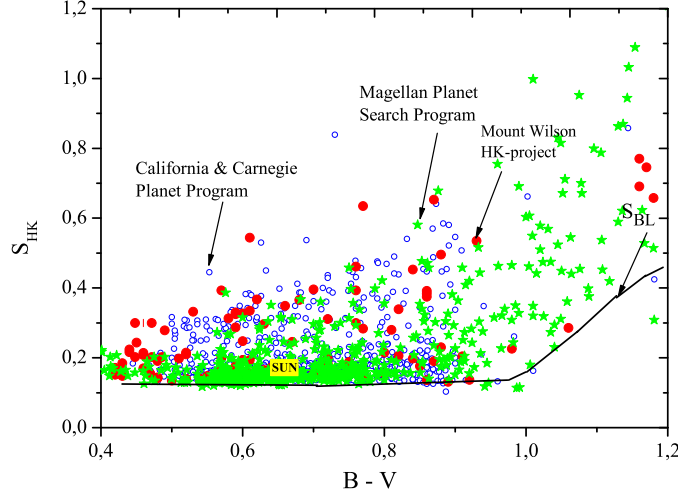


Fig. 2. Chromospheric activity of F, G, K and M stars from three observational Programs.

In Sun-like stars of late spectral classes, X-rays are generated by the magnetically confined plasma known as the corona (see Vaiana et al. 1981), which is heated by the stellar magnetic dynamo. The observed decrease of the X-ray emission between pre-main sequence young stars and older stars can be attributed to the rotational spin-down of a star, driven by mass loss through a magnetized stellar wind (Skumanich 1972).

The magnetic fields of the Sun and solar-type stars are believed to be generated by flows of conductive matter. Such processes are commonly called a hydromagnetic dynamo or simply a dynamo.

The main parameter of solar and stellar dynamo models is the dynamo number  $D = \alpha \Omega R^3 / \eta^2$ , where  $\Omega$  is the rotation rate of a star,  $R$  is its radius,  $\eta$  is the effective magnetic diffusivity, and the parameter  $\alpha$  defines the intensity of field generation by the cyclonic convection (see Parker 1955; Vainshtein et al. 1980). The generation of magnetic fields is ultimately governed by hydrodynamic processes in stellar convection zones. The Sun's radiative interior is surrounded by a convection zone that occupies the outer 30% by radius; in most part of this region the angular velocity  $\Omega$  is constant on conical surfaces and there is a balance between Coriolis and baroclinic effects. At the base of the convection zone there is an abrupt transition in the tachocline to the almost uniformly rotating radiative zone. Superimposed on this pattern are zonal shear flows (torsional oscillations) that vary with the solar cycle, appearing as a branch of enhanced rotational velocity that coincides with the activity belt on the Sun and solar-type stars. As expected, the torsional oscillations on the Sun have an 11-year period, a half of the underlying magnetic 22-year cycle. The main implications of dynamo theory, as applied to stars, has revealed the main features of the cyclic behavior in the Sun and stars, but it involves ad hoc assumptions, that helps us to compare the dynamo theory results with observations.

The nonlinear dynamo model allows to explain the phenomenon of the irregular appearance of the periods of Grand minima along with the regular cycles of activity. In the nonlinear dynamo theory there is an important parameter – the critical dynamo number  $D_C$  for the field generation. The magnetic field decays for  $D$  below its critical value namely, when  $D < D_C$  and rises with time for  $D > D_C$ . In a certain range of dynamo numbers, two types of solutions are possible: decaying oscillations of weak fields (known as Maunder minimum in solar observations) and magnetic cycles with a constant and large amplitude (known as the standard 11-year cycles), see Kitchatinov & Olemskoy (2010).

The rotation rate of the Sun and solar-type stars decreases with time (Skumanich, 1972), with a feedback existing between the dynamo and rotation: the higher the magnetic activity, is the larger the rate of angular momentum loss. The reducing of the spin rate may ultimately bring the stars to the threshold of large-scale dynamo action. The states of low activity are actually observed only in old stars (Wright et al., 2004). If the proposed picture is valid, then observations can reveal a sharp decrease in reducing of the spin rates for old stars that exhibit grand minima of activity.

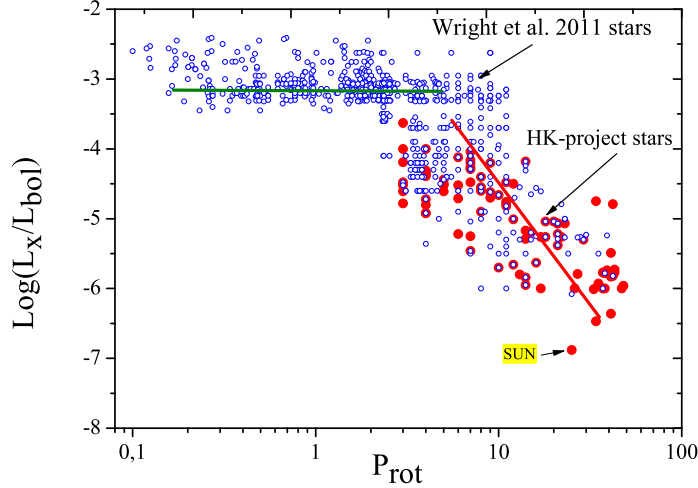


Fig. 3. X-ray to bolometric luminosity ratio plotted against rotation period.

A relationship between the stellar rotation and the X-ray luminosity  $L_X$  was first described by Pallavicini et al. (1981). In Figure 3 we show the  $\log(L_X/L_{bol})$  versus  $P_{rot}$  for stars from the catalogue of stars, the details of which are presented in Wright et al. (2011) - open circles, and for the stars of the HK-project presented in Baliunas et al. (1995) - filled circles. In Wright et al. (2011) there was done the conversion of all X-ray luminosities of the stars from the catalogue of 824 stars to the ROSAT 0.1-2.4 keV energy band. The selected data of X-ray luminosities  $L_X/L_{bol}$  of 80 HK-project stars was also taken from the ROSAT All-Sky Survey (Bruevich et al. 2001). This sample also includes the Sun using the values of  $\log L_X/L_{bol} = -6.88$  (for medium level of activity) and  $P_{rot} = 26.09$ . Figure 3 demonstrates that there are two main regimes of coronal activity: a linear regime where activity increases with decreasing the rotation period, and a saturated regime where the X-rays luminosity ratio is constant with  $\log(L_X/L_{bol}) = -3.13$  (see Wright et al. 2011, Wright et al. 2013).

We can see that the HK-project stars which are not enough young and active, belong to stars of linear regime in Figure 3. We can also note that the Sun confirms its place among Sun-like stars: it has relatively low level of X-rays luminosity among all the stars in the studied sample.

Below in Figure 7b we also show the place of the solar coronal activity among the coronal activity of stars of the HK-project. It can be noted that the Sun is at the place with absolutely lowest level of coronal activity among Sun-like HK-project stars.

One can also note that solar photometric radiation changes very little in the activity cycle, less than 0.1 %. The simultaneous monitoring of photometric and chromospheric H&K CaII emission data series of stars similar to the Sun in age and average activity level showed that there is an empirical correlation between the average stellar CA level and the photometric variability. In general, more active stars show larger photometric variability. The Sun is significantly less variable that indicates by the empirical relationship, see Shapiro et al. (2013). It was found that on a long time scale the position of

the Sun on the diagram of photometric variability versus CA changers is not constant in time. So Shapiro et al. (2013) suggested that the temporal mean solar variability might be in agreement with stellar data.

But at present we can see that the Sun confirms its unique place among Sun-like stars: its photometric variability is unusually small. The observational verification has confirmed in Lockwood et al. (2007): the Lowell observatory photometric observations of 33 stars of the HK-project revealed the fact that the photometric variability of the Sun during the cycle of magnetic activity is much less than the photometric variability of other HK-project stars.

### 3 OBSERVATIONS OF HK-PROJECT STARS

It can be noted that among the databases of observations of Sun-like stars with known values of  $S_{HK}$  the sample of stars of the HK-project was selected most carefully in order to study stars which are analogues of the Sun. Moreover, unlike different Planet Search Programs of observations of Sun-like stars, the Mount Wilson Program was specifically developed for a study of a Sun-like cyclical activity of main sequence F, G and K-stars (single) which are the closest to the "young Sun" and "old Sun".

The duration of observations (more than 40 years) in the HK-project has allowed to detect and explore the cyclical activity of the stars, similar to 11-yr cyclical activity of the Sun. First O. Wilson began this program in 1965. He attached great importance to the long-standing systematic observations of cycles in the stars. Fluxes in passbands of 0.1 nm wide and centered on the CaII H&K emission cores have been monitored in 111 stars of the spectral type F2-K5 on or near main sequence on the Hertzsprung-Russell diagram (see Baliunas et al. 1995; Radick et al. 1998; Lockwood et al. 2007).

For the HK-project, stars were carefully chosen according to those physical parameters, which are most close to the Sun: cold, single stars – dwarfs, belonging to the main sequence. Close binary systems are excluded.

Results of joint observations of the HK-project radiation fluxes and periods of rotation gave the opportunity for the first time in stellar astrophysics (Noyes et al. 1984) to detect the rotational modulation of the observed fluxes. This meant that on the surface of a star there are inhomogeneities those are living and evolving in several periods of rotation of the stars around its axis. In addition, the evolution of the periods of rotation of the stars in time clearly pointed to the fact of existence of the star's differential rotations similar to the Sun's differential rotations.

The authors of the HK-project with use of frequency analysis of the 40-year observations have discovered that the periods of 11-yr cyclic activity vary little in size for the same star (Baliunas et al. 1995; Lockwood et al. 2007). Durations of cycles vary from 7 to 20 years for different stars. It was shown that stars with cycles represent about 30 % of the total number of studied stars.

### 4 CYCLIC ACTIVITY OF HK-PROJECT STARS. FROM PERIODOGRAM TO WAVELET ANALYSIS.

The evolution of active regions on a star on a time scale of about 10 years determines the cyclic activity similar to the Sun.

For 111 HK-project stars the, periodograms were computed for each stellar record in order to search for activity cycles (Baliunas et al. 1995). The significance of the height of the tallest peak of the periodogram was estimated by the false alarm probability (FAP) function (see Scargle 1982). The stars with cycles were classified as follows: if for the calculated  $P_{cyc} \pm \Delta P$  the FAP function  $\leq 10^{-9}$  then this star is of the "Excellent" class ( $P_{cyc}$  is the period of the cycle). If  $10^{-9} \leq FAP \leq 10^{-5}$  then this star is of the "Good" class. If  $10^{-5} \leq FAP \leq 10^{-2}$  then this star is of the "Fair" class. If  $10^{-2} \leq FAP \leq 10^{-1}$  then this star is of the "Poor" class.

In Baliunas et al. (1995); Radick et al. (1998); Lockwood et al. (2007) the regular chromospheric cyclical activity of HK-project Sun-like stars were studied through the analysis of the power spectral density with the Scargle's periodogram method (Scargle 1982). It was pointed out that the detection of

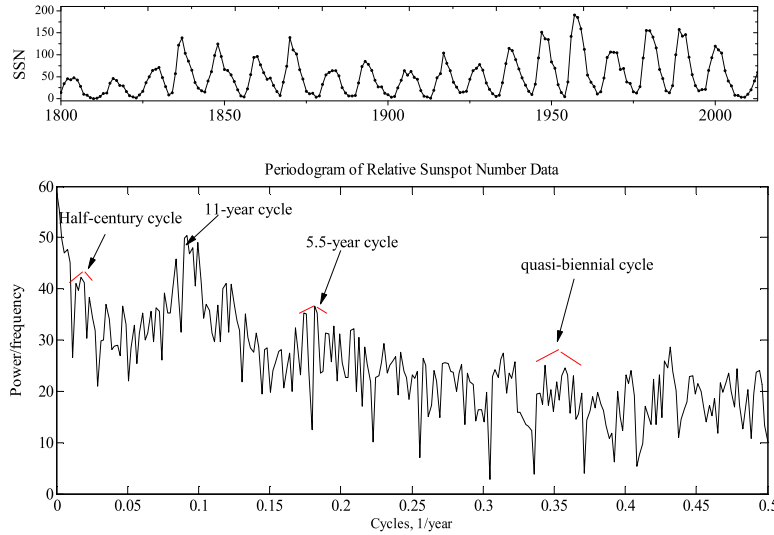


Fig. 4. The periodogram of the yearly averaged relative sunspot numbers for 1800 – 2013 observations.

a periodic signal hidden by a noise is frequently a goal in astronomical data analysis. So, in Baliunas et al. (1995) the periods of HK-project stars activity cycles similar to 11-yr solar activity cycle were determined. The significance of the height of the tallest peak of the periodogram was estimated by the false alarm probability (FAP) function. Among the 50 stars with detected cycles, only 13 stars (with the Sun), which are characterized by the cyclic activity of the "Excellent" class, have been found.

We have illustrated the method of cyclic period calculation with Scargle's periodogram technique on the example of the Sun. We obtained the periodogram of the yearly averaged relative sunspot number or SSN – Solar Sunspot Number for observations conducted in 1800 – 2013.

In Figure 4 we present the relative sunspot number yearly averaged data set (top panel). It is known that direct observations of sunspots were made only since 1850, and from 1700 to 1850 the sunspots data have been taken from indirect estimates. This fact, as we will see below in Figure 5a, affects the quality of time-frequency analysis for 1700 - 1850 data.

In Figure 4 we show the Scargle's periodogram of the relative sunspot number for 1800 - 2013 data set (presented in bottom panel). Our sample periodogram in Fig. 4 shows that the main period of cycles is equal approximately to 11 years. The level of the Power/Frequency or Power Spectral Density (PSD) as function of frequency (1/year) for these observational data shows that the PSD value for the 11-year cycle is 2 times greater than for nearby PSD values. The fact that the peak of the 11-year periodicity is not very sharp shows that the period of the 11-year cycle is not constant: it changes (for 2 centuries of observations) from 10 to 12 years. In Figure 4 we marked the peaks corresponding to the periods of the second order of smallness: a half-century cycle phenomena which were first discovered by Vitinsky et al. (1986), 5-5 -year and quasi-biennial cycles. The half-century cycle and 5-5 peaks are not much pronounced (some of percent) against the neighboring signals. The quasi-biennial peak (due to the fact that he's very weak on power and is blurred due to the evolution of the period from 3.5 to 2 years within a single 11-year cycle) is in general at the noise level. As one can see, the very obvious peak of PSD, which corresponds to the 11-year cycle, has a value only about 2 times greater than the surrounding background.

We can see that, unfortunately, this method allows us only to define a fixed set of main frequencies (that determines the presence of significant periodicities in the series of observations). In the case where values of periods change significantly during the interval of observations, the accuracy of determina-



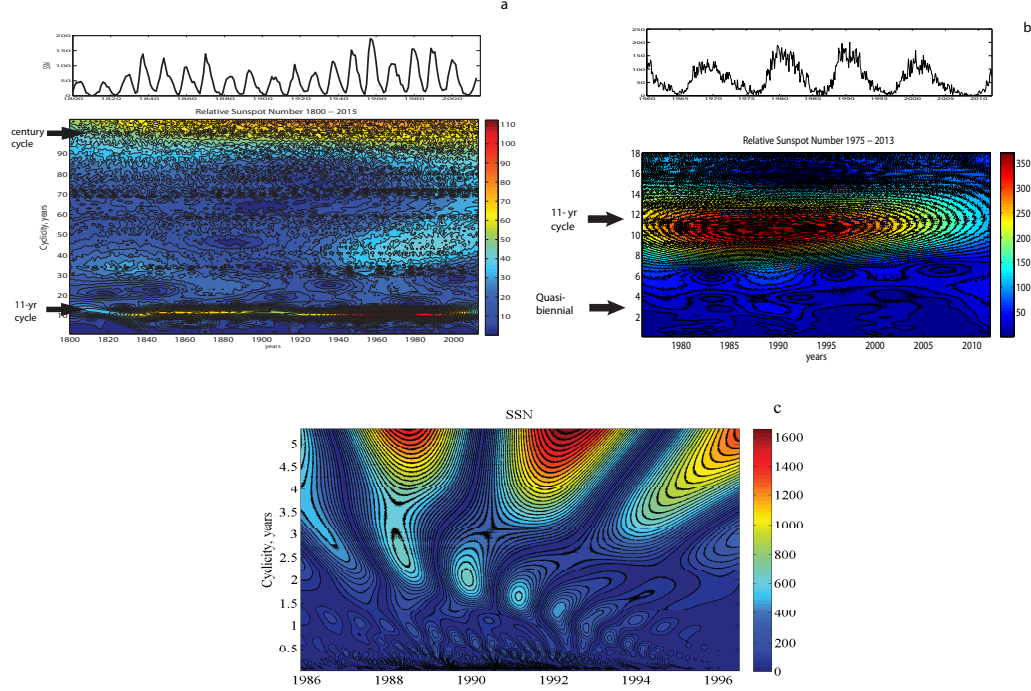


Fig. 5. Wavelet analysis of the relative sunspot numbers: (a) yearly averaged observations from 1700 to 2012; (b) monthly averaged observations from 1950 to 2012; (c) daily observations in 22-nd solar activity cycle.

tion of periods becomes worse. It is also impossible to obtain information about the evolution of the periodicity in time.

In Kollath & Olah (2009), different methods, such as short-term Fourier transform, wavelet, and generalized time-frequency distributions, have been tested and used for analyzing temporal variations in timescales of long-term observational data which have information on the magnetic cycles of active stars and that of the Sun. It was shown that the application of the wavelet analysis is preferable when studying a series of observations of the Sun and stars. Their time-frequency analysis of multi-decadal variability of the solar Schwabe (11-yr) and Gleissberg (century) cycles during the last 250 years showed that one cycle (Schwabe) varies between limits, while the longer one (Gleissberg) continually increases. By analogy from the analysis of the longer solar record, the presence of a long-term trend may suggest an increasing or decreasing of a multi-decadal cycle that is presently unresolved in stellar records of short duration.

A wavelet technique has become popular as a tool for extracting a local time-frequency information. The wavelet transform differs from the traditional time-frequency analysis (Fourier analysis, Scargle's periodogram method) because of its efficient ability to detect and quantify multi-scale, non-stationary processes (Frick et al. 1997). The wavelet transform maps a one-dimensional time series  $f(t)$  into the two-dimensional plane, related to time and frequency scales. Wavelets are the localized functions which are constructed based on one so-called mother wavelet  $\psi(t)$ . The choice of wavelet is dictated by signal or image characteristics and the nature of the application. Understanding properties of the wavelet analysis and synthesis, you can choose a mother wavelet function that is optimized for your application. Thus, we choose a complex Morlet wavelet which depends on two parameters: a bandwidth parameter and a wavelet center frequency. The Morlet wavelet allows one to get results with better spectral resolution. The Morlet mother wavelet function can be represented as  $\psi(t) = e^{-t^2/a^2} e^{i2\pi t}$ .

The standard algorithm of wavelet analysis as applied to astronomical observations of the Sun and stars was discussed in detail in Frick et al. (1997), Kollath & Olah (2009). The choice of the Morlet



wavelet as the best mother wavelet  $\psi(t)$  for astronomical data processing is discussed in Bruevich et al. (2014) on the basis of comparative analysis of results obtained using different mother wavelets.

The results of our solar data wavelet analysis are presented on the time-frequency plane (Figures 5a,b,c). The notable crowding of horizontal lines on the time-frequency plane around the specific frequency indicates that the probability of existence of stable cycles is higher for that frequency (cycle's duration) in accordance with the gradient bar to the right.

In Figure 5 the results of the continuous wavelet transform analysis (with help of Morlet mother wavelet) of time series of SSN are presented: Fig 5a corresponds to yearly averaged data, Fig 5b corresponds to monthly averaged data, Fig 5c corresponds to daily data. The (X, Y) plane is the time-frequency plane of calculated wavelet-coefficients  $C(a, b)$ : a-parameter corresponds to Y plane (Cyclicity, years), b-parameter corresponds to X plane (Time, years). The modules of  $C(a,b)$  coefficients, characterizing the probability amplitude of regular cyclic component localization exactly at the point (a, b), are laid along the Z axis. In Figure 5 we see the projection of  $C(a,b)$  to (a, b) or (X, Y) plane. This projection on the plane (a, b) with isolines allows to trace changes of the coefficients on various scales in time and reveal a picture of local extrema of these surfaces. It is the so-called skeleton of the structure of the analyzed process. We can also note that the configuration of the Morlet wavelet is very compact in frequency, which allows us to determine the localization of instantaneous frequency of observed signal most accurately (compared to other mother wavelets).

Figure 5a presents the results of wavelet analysis of the same yearly averaged sunspot number data set as in Figure 4. The cycles with century, half-century and 11-yr durations are marked with arrows. In Figure 5b we show the results of wavelet analysis of the monthly averaged sunspot number data set. The cycles with 11-yr and quasi-biennial durations are also marked with arrows. Note that for the study of cycles on a shorter time scale (Figure 5b) we use more detailed observations of the Sun.

Figure 5a confirms the known fact that the period of the main solar activity cycle is about 11-yr in the XIX century and is about 10 yr in the XX century. It is also known that the abnormally long 23-rd cycle of solar activity ended in 2009 and lasted about 12.5 years. We can see all this facts in Figures 5a,b. Thus, it can be argued that the value of a period of the main cycle of solar activity for past 200 years is not constant and varies by 15-20 %.

In Figure 5c we show the results of wavelet analysis of daily SSN data in the solar cycle 22. We analysed that data on the time scale which is equal to several years and identified the second order periodicity such as 5.5 years and quasi-biennial as well as their temporal evolution.

In Olah et al. (2009) a study of time variations of cycles of 20 active stars based on decades (long photometric or spectroscopic observations) with a method of time-frequency analysis was done. They found that cycles of sun-like stars show systematic changes. The same phenomenon can be observed for the cycles of the Sun.

Olah et al. (2009) found that fifteen stars definitely show multiple cycles, the records of the rest are too short to verify a timescale for a second cycle. For 6 HK-project stars (HD 131156A, HD 131156B, HD 100180, HD 201092, HD 201091 and HD 95735) the multiple cycles were detected. Using wavelet analysis the following results (other than periodograms from Baliunas et al., 1995) were obtained:

HD 131156A shows variability on two time scales: the shorter cycle is about 5.5-yr, a longer-period variability is about 11 yr.

For HD 131156B only one long-term periodicity has been determined.

For HD 100180 the variable cycle of 13.7-yr appears in the beginning of the record; the period decreases to 8.6-yr by the end of the record. The results in the beginning of the dataset are similar to those found by Baliunas et al. (1995), who found two cycles, which are equal to 3.56 and 12.9-yr.

The record for HD 201092 also exhibits two activity cycles: one is equal to 4.7-yr, the other has a time scale of 10-13 years.

The main cycle, seen in the record of HD 201091, has a mean length of 6.7-yr, which slowly changes between 6.2 and 7.2-yr. A shorter, significant cycle is found in the first half of the record with a characteristic time scale of 3.6-yr.

The stronger cycle of HD 95735 is 3.9-yr. A longer, 11-yr cycle is also present with a smaller amplitude.

In our paper we have applied the wavelet analysis for partially available data from the records of relative CaII emission fluxes - the variation of  $S_{HK}$  for 1965-1992 observation sets from Baliunas et al. (1995) and for 1985-2002 observations from Lockwood et al. (2007). We used the detailed plots of  $S_{HK}$  time dependencies: each point of the record of observations, which we processed in this paper using wavelet analysis technique, corresponds to three months averaged values of  $S_{HK}$ .

In this paper we have studied 5 HK-project stars with cyclic activity of the "Excellent" class: HD 10476, HD 81809, HD 103095, HD 152391, HD 160346 and the star HD 185144 with no cyclic activity.

We used the complex Morlet wavelet 1.5 - 1 which can most accurately determine the dominant cyclicity as well as its evolution in time in solar data sets at different wavelengths and spectral intervals (Bruevich & Yakunina 2015).

We hope that wavelet analysis can help to study the temporal evolution of CA cycles of the stars. Tree-month averaging also helps us to avoid the modulation of observational  $S_{HK}$  data by star's rotations.

In Figure 6 we present our results for cycles of 6 HK-project stars:

HD 81809 has a mean cycle duration of 8.2-yr, which slowly changes between 8.3-yr in the first half of the record and 8.1-yr in the middle and the end of the record while Baliunas et al. (1995) found 8.17-yr.

HD 103095 has a mean cycle duration of 7.2-yr, which slowly changes between 7.3-yr in the first half of the record, 7.0-yr in the middle and 7.2-yr in the end of the record while Baliunas et al. (1995) found 7.3-yr.

HD 152391 has a mean cycle duration of 10.8-yr, which slowly changes between 11.0-yr in the first half of the record and 10.0-yr in the end of the record while Baliunas et al. (1995) found 10.9-yr.

HD 160346 has a mean cycle duration of 7.0-yr which does not change during the record in agreement with Baliunas et al. (1995) estimated 7.0-yr.

HD 10476 has a mean cycle duration of 10.0-yr in the first half of the record, then it sharply changes to 14-yr, while Baliunas et al. (1995) found 9.6-yr. After changing the high amplitude cycle's period from 10-yr to 14-yr in 1987, the low amplitude cycle remained with 10.0-yr period - we can see two activity cycles. Baliunas et al. (1995) estimated HD 10476 cycle as 9.6-yr.

HD 185144 has a mean cycle duration of 7-yr which changes between 8-yr in the first half of the record and 6-yr in the end of the record while Baliunas et al. (1995) haven't found the well-pronounced cycle.

In Olah et al. (2009), the multiple cycles were found for HD 13115A, HD 131156B, HD 93735 stars, for which no cycles have been found in Baliunas et al. (1995). For the stars of the "Excellent" class HD 201091 and HD 201092, cycle periods found in Baliunas et al. (1995) were confirmed and the shorter cycles (similar to solar quasi-biennial) were also determined.

Olah et al. (2009) have concluded that all the stars from their pattern of cool main sequence stars have cycles and most of the cycle durations change systematically.

However we can see that the stars of the "Excellent" class have relatively constant cycle durations - for these stars the cycle's periods calculated in Baliunas et al. (1995) and cycle's periods found with the use of the wavelet analysis are the same.

A similar picture can be seen for the Sun: the long-term behaviour of the sunspot group numbers has been analysed using a wavelet technique by Frick et al. (1997) who plotted changes of the Schwabe cycle (length and strength) and studied the grand minima. The temporal evolution of the Gleissberg cycle can also be seen in the time-frequency distribution of the solar data. According to Frick et al. (1997), the Gleissberg cycle is as variable as the Schwabe cycle. It has two higher amplitude occurrences: the first one is around 1800 (during the Dalton minimum), and the next one is around 1950. They found very interesting fact - the continuous decrease in the frequency (increase of period) of the Gleissberg cycle. While near 1750 the cycle duration was about 50 yr, it lengthened to approximately 130 yr by 1950.

In the late part of the XX century, some of solar physicists began to examine with different methods the variations of relative sunspot numbers not only in the high amplitude 11-yr Schwabe cycle but in low amplitude cycles approximately equal to half (5.5-yr) and fourth (quasi-biennial) parts of the period of the main 11-yr cycle, see Vitinsky et al. (1986). The periods of the quasi-biennial cycles vary

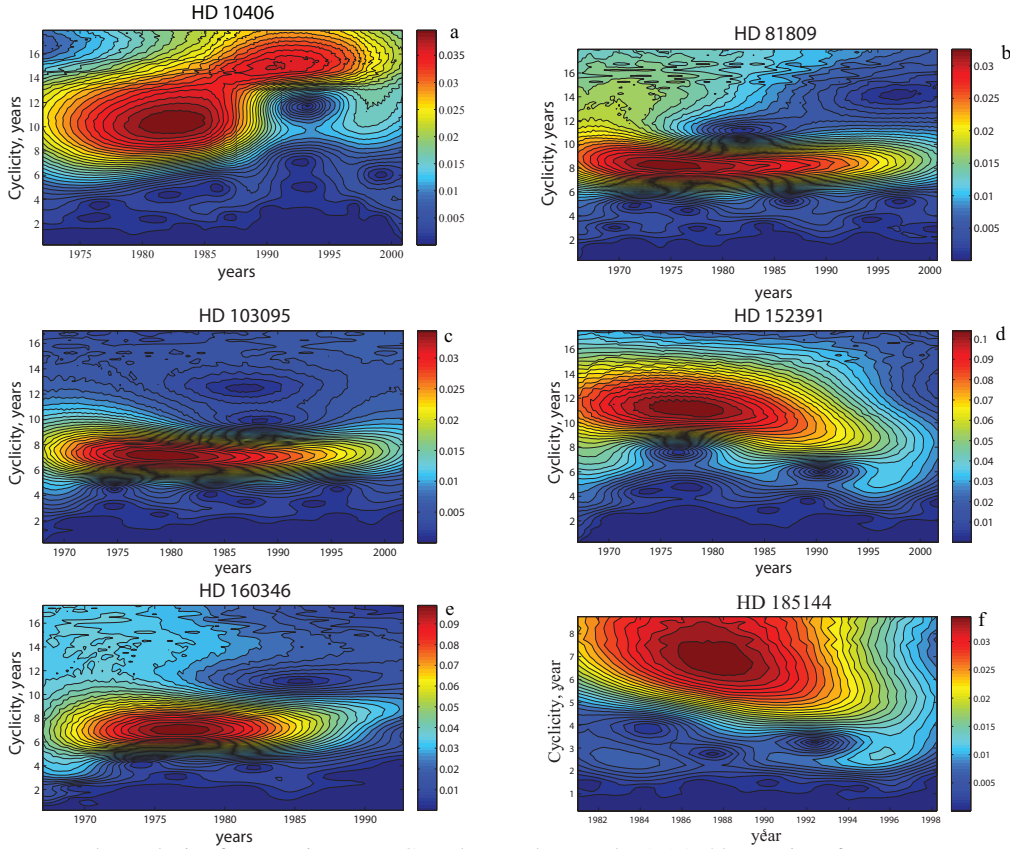


Fig. 6. Wavelet analysis of HK-project stars. Complex Morlet wavelet 1.5-1. Observations from 1969 to 2002: (a) HD 10476, (b) HD 81809, (c) HD 103095, (d) HD 152391, (e) HD 160346, (f) HD 185144.

considerably within one 11-yr cycle, decreasing from 3.5 to 2 yrs (see Figure 5b,c), which complicates a study of such periodicity with the periodogram method.

Using methods of frequency analysis of signals, the quasi-biennial cycles have been studied not only for the relative sunspot number, but also for 10.7 cm solar radio emission and for some other indices of solar activity, see Bruevich & Yakunina (2015). It was also shown that the cyclicity on the quasi-biennial time scale often takes place among stars with 11-yr cyclicity, see Bruevich & Kononovich (2011).

The cyclicity similar to the solar quasi-biennial was also detected for Sun-like stars from direct observations. In Morgenthaler et al. (2011), results of direct observations of magnetic cycles of 19 Sun-like stars of F, G, K spectral classes within 4 years were presented. Stars of this sample are characterized by masses between 0.6 and 1.4 of the solar mass and by rotation periods between 3.4 and 43 days. Observations were made using NARVAL spectropolarimeter (Pic du Midi, France) between 2007 and 2011. It was shown that for the stars of this sample  $\tau$  Boo and HD 78366 (the same of the Mount Wilson HK-project) the cycle lengths derived by CA by Baliunas et al. (1995) seem to be longer than those derived by spectropolarimetry observations of Morgenthaler et al. (2011). They suggest that this apparent discrepancy may be due to the different temporal sampling inherent to these two approaches, so that the sampling adopted at Mount Wilson may not be sufficiently tight to unveil short activity cycles. They hope that future observations of Pic du Midi stellar sample will allow them to investigate longer time scales of the stellar magnetic evolution.

For the Sun-like F, G and K stars according to *Kepler* observations, "shorter" chromosphere cycles with periods of about two years have also been found (see Metcalfe et al. 2010; Garcia et al. 2010).

We assume that precisely these quasi-biennial cycles were identified in Morgenthaler et al. (2011):  $\tau$  Boo and HD 78366 are the same of the HK-project, these stars have cycles similar to the quasi-biennial solar cycles with periods of a quarter of the duration of the periods defined in Baliunas et al. (1995).

Note, that in case of the Sun, the amplitude of variations of the radiation in quasi-biennial cycles is substantially less than the amplitude of variations in main 11-yr cycles. We believe that this fact is also true for all Sun-like stars of the HK-project and in the same way for  $\tau$  Boo and HD 78366.

The quasi-biennial cycles cannot be detected with the Scargle's periodogram method. But methods of spectropolarimetry from Morgenthaler et al. (2011) allowed detecting the cycles with 2 and 3-yr periods. Thus, spectropolarimetry is more accurate method for detection of cycles with different periods and with low amplitudes of variations.

So, the need for wavelet analysis of HK-project observational data is dictated also by the fact that the application of the wavelet method to these observations will help: (1) to find cyclicities with periods equal to a half and a quarter from the main high amplitude cyclicity; (2) to clarify periods of high amplitude cycles and to follow their evolution in time; (3) to find other stars with cycles for which cycles were not determined using the periodogram method due to strong variations of the period as in the case of HD 185144.

The analysis of cyclic activity of Sun-like stars using Scargle's periodogram method in Baliunas et al. (1995) and wavelet analysis simultaneously showed that the ranking of stars into classes according to the quality of their cycles ("Excellent", "Good", "Fair" and "Poor") is very important moment in the study of stellar cycles.

Wavelet analysis helped us to understand why stars of "Fair" and "Poor" classes differ from stars of "Excellent" and "Good" classes: the main peak on their periodograms is greatly expanded due to strong variations of the cycle's duration.

As it turned out, the differentiation of stars with cycles into "Excellent", "Good", "Fair" and "Poor" classes is very important: stars with stable cycles ("Excellent" and "Good") and stars with unstable cycles ("Fair" and "Poor") relate to different groups in the graphs of dependencies  $\log R'_{HK}$  versus  $(B - V)$ ,  $\log L_X/L_{Bol}$  versus  $(B - V)$ ,  $P_{cyc}$  versus Age, see Figure 7 and Figure 8 below.

## 5 CHROMOSPHERIC AND CORONAL ACTIVITY OF HK PROJECT STARS OF DIFFERENT SPECTRAL CLASSES WITH CYCLES

Processes, that determine complex phenomena of stellar activity and cover practically the whole atmosphere from the photosphere to the corona, occur differently among Sun-like stars belonging to different spectral classes.

The Mount Wilson HK project observational data allow us to study the Sun-like cyclic activity of stars simultaneously with their chromospheric and coronal activity. The selected data of X-ray luminosities  $\log L_X/L_{Bol}$  of 80 HK-project stars were taken from the ROSAT All-Sky Survey, see Bruevich et al. (2001).

As noted earlier by (Baliunas et al. 1995; Lockwood et al. 2007), the average CA of the stars, or rather the values of  $S_{HK}$  and also of  $\log R'_{HK}$  varies (increases) with the increase of the color index  $(B - V)$ , see Figure 2, Figure 7a.

Our polynomial regression analysis of HK-project stars showed that there is a relation which is described by the following formula:

$$\log R'_{HK} = -5.03 + 0.637 \cdot (B - V) - 0.358 \cdot (B - V)^2 \quad (1)$$

Let us denote the right part of the relation (1) as  $F(B - V)$ .

We consider the stars which have  $\log R'_{HK} > F(B - V)$  to be characterized by the high level of the CA, and stars with  $\log R'_{HK} \leq F(B - V)$  – by the low level of the CA, see Figure 7a.

Next, we have analysed all 110 stars from the HK-project and the Sun to determine which kind of the level of the CA corresponds to one or another star. We will consider these results further in the comparative analysis of stars of different spectral classes, see Table 1.

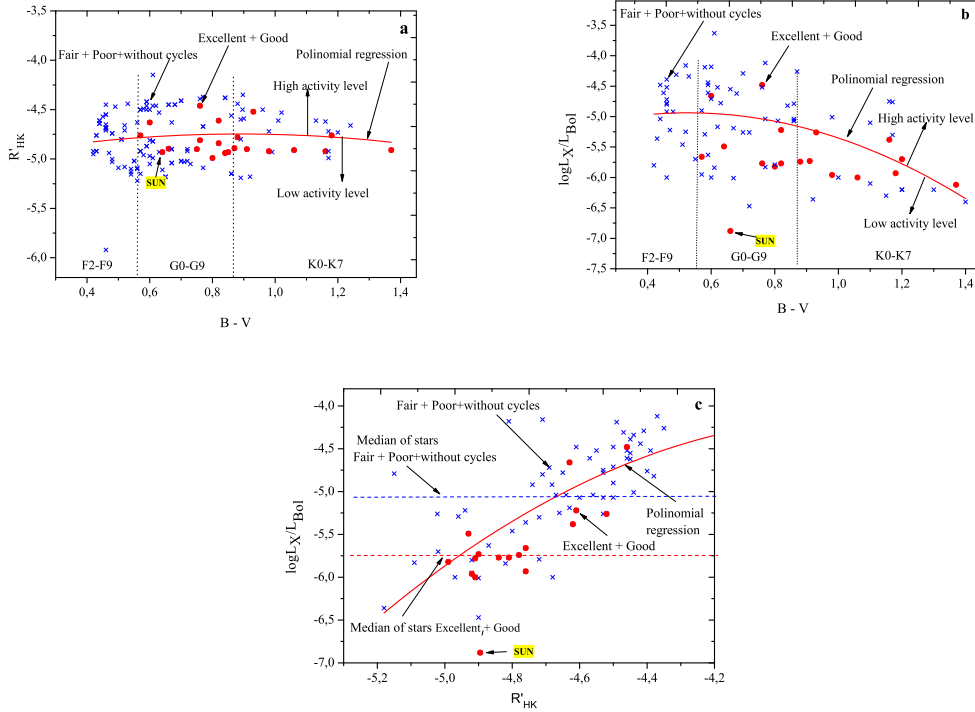


Fig. 7. HK-project stars. Observations from 1969 to 1994 yrs. (a)  $\log R'_{HK}$  versus  $(B - V)$ , (b)  $\log L_X/L_{Bol}$  versus  $(B - V)$ , (c)  $\log L_X/L_{Bol}$  versus  $\log R'_{HK}$ . Solid line – polynomial regression, "Excellent" + "Good" stars – filled circles, "Fair" + "Poor" stars and stars without cycles – crosses. Dashed lines – median values for stars of "Fair" + "Poor" + "Var" classes (top dashed line) and "Excellent" + "Good" classes (lower dashed line).

For 80 stars, the coronal radiation of which we know from the ROSAT data, we also do polynomial regression analysis and obtain the following relationship between the X-ray luminosity, normalized to the bolometric luminosity, and the color index  $(B - V)$ :

$$\log L_X/L_{Bol} = -5.45 + 1.95 \cdot (B - V) - 1.85 \cdot (B - V)^2 \quad (2)$$

Let us denote the right hand side of the relation (2) as  $P(B - V)$ . By analogy with the analysis of the CA of stars, we consider the stars with  $\log L_X/L_{Bol} > P(B - V)$  to be characterized by the high level of the coronal activity, and stars with  $\log L_X/L_{Bol} \leq P(B - V)$  – by the low level of the coronal activity, see Figure 7b.

As noted above, in the case of the CA a direct correlation takes place: with the increase of the color index  $(B - V)$  the average value of CA defined as  $S_{HK}$  increases, see Isaacson et al. (2010). When we use  $\log R'_{HK}$  as the index of the CA we see the other trend – with the increase of the color index  $(B - V)$  the average value of  $\log R'_{HK}$  is almost constant, see Figure 7a. When we consider the dependence of the X-ray radiation of stars from  $(B - V)$ , the inverse correlation takes place: with the increase of the color index  $(B - V)$ , the average value of  $\log L_X/L_{Bol}$  decreases, see Figure 7b.

Figures 7a, 7b also demonstrate that stars with cycles of "Excellent" and "Good" classes are mostly characterized by the low level of the chromospheric and coronal activity (about 70 %), as opposed to stars with cycles of "Fair" and "Poor" classes which are mostly characterized by the high level of the chromospheric and coronal activity (about 75 %).

Note that most of stars, characterized by increased CA, have also increased coronal activity. About 15 % of stars, including the Sun, are characterized by the coronal activity that is significantly lower than

**Table 1** Comparative analysis of cycles of stars and the quality of their cyclicities for stars of different spectral classes.

Interval of spectral classes	F2 -F9	G0 -G9	K0 -K7
$\Delta(B - V)$	0.42 -0.56	0.57 -0.87	0.88 -1.37
Total number of stars in spectral interval	39	44	27
Number of stars with known values $L_X/L_{Bol}$	26	32	22
Relative number of stars with increased coronal activity	61 %	42 %	36 %
Relative number of stars with increased CA	56%	46 %	48 %
Relative number of stars with CA cycles	25%	40%	72%
Quality of chromospheric cycles "Excell+Good"/"Fair+Poor"	0/10	7/10	14/4

the value which should correspond to its CA, see Figure 7c. The regression line in Figure 7c divides the stars with relatively high and relatively low  $\log L_X/L_{Bol}$ . It is seen that the stars with no cycles ("Var") and the stars with poorly pronounced cyclical activity ("Fair" + "Poor") are characterized by relatively high fluxes of coronal radiation (median value corresponds to the value of  $\log L_X/L_{Bol} = -5.05$ ). The stars, belonging to classes "Excellent" + "Good", are on average characterized by lower level fluxes of coronal radiation (a median value corresponds to the value of  $\log L_X/L_{Bol} = -5.75$ ).

The existence or absence of a pronounced cyclicity, as well as the quality of the identified cycles (belonging to classes "Excellent", "Good", "Fair", "Poor"), for F, G and K stars varies significantly, see Table 1.

Bruevich et al. (2001) noted the difference between stars of "Excellent", "Good", "Fair" and "Poor" classes from a position of presence and degree of development of under photospheric convective zones of stars of different color index ( $B - V$ ).

In Table 1 we can see that for our sample of HK-project stars the coronal activity is higher in stars of the spectral class F, due to their total increased atmospheric activity (as compared to stars of spectral classes G and K). This conclusion is consistent with the findings of Kunte et al. 1988 in which it was found that  $\log L_X/L_{Bol}$  is well correlated (decreases) with the age of stars. But on the other hand, G and K HK-project stars in our study are older than F stars that is evident from their slower rotation.

Thus, we can note here (illustrated below in Table 1) that the quality of CA cycles (the ratio of the total number of stars belonging to classes with a well-defined cyclicity "Excellent" + "Good" to the number of stars with less than a certain cyclicity "Fair" + "Poor") essentially differs for stars of different spectral classes F, G and K.

Different tests of the dependency of the cycle period (with durations in various time scales from seconds in the asteroseismic analysis to several yrs in Dynamo processes studies) on different parameters of Sun-like stars have been performed, see Morgenthaler et al. (2011); Garcia et al. (2010); Garcia et al. (2014); Mathur et al. (2012); Metcalfe et al. (2010).

We have analysed the dependence of the star magnetic cycle duration on their ages. Cycle durations were taken from Baliunas et al. (1995). Unfortunately, we have very limited stellar sample (Lockwood et al. 2007). Stellar ages were calculated according to Wright et al. (2004) as a function of the CA.

In Figure 8, the connection of  $P_{cyc}$  with ages of stars is shown. The scatter of points around the regression line is very large. For stars with cycles of "Excellent" + "Good" classes with the increase of the age (or various parameters connected with the age) the duration of cycles increases by about 20 % with an increase of  $\log(\text{Age/yr})$  from 8.5 to 10. The stars with cycles of "Fair" + "Poor" classes show no dependence of  $P_{cyc}$  on age.

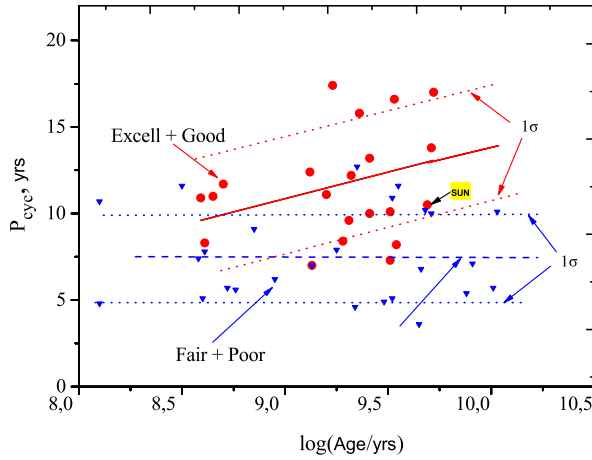


Fig. 8.  $P_{cyc}$  versus stellar age for the stars of the HK-project. The regressions for the full sample (the lower dashed line) and for stars with cycles of the "Excellent" + "Good" classes (the upper solid line) are shown. For both regressions the dotted lines indicate the intervals corresponding to  $1\sigma$  standard deviation.

For carrying out a high quality examination of cycles for Sun-like stars, the problem of determination of  $P_{cyc}$  as accurately as possible, using frequency-time (wavelet) analysis, becomes very actual.

## 6 CONCLUSIONS

- The quality of the cyclic activity, similar to the solar 11-yr one, is significantly improved (from "Fair + Poor" to "Excellent + Good") in G and K-stars as compared to F-stars. The F-stars 11-yr cyclicity (detected only in every fourth case) is determined with a lower degree of reliability.
- We show that for the interpretation of observations the use of modern methods of wavelet analysis is required. The nature of the cyclic activity of Sun-like stars is very similar to the Sun's one: along with main cycles there are quasi-biennial cycles. Periods of solar quasi-biennial cycles evolve during one main 11-yr cycle from 2 to 3.5 yrs that complicates their detection with the periodogram technique. Our conclusion about quasi-biennial cycles for stars is supported by the direct observation of cycles with the duration of 2-3 yrs for  $\tau$  Boo and HD 78366 by Morgenthaler et al. (2011) and earlier detection of cycles with durations of 11.6 and 12.3 yrs by Baliunas et al. (1995) for the same stars.
- The level of CA of the Sun is consistent with that of HK-project stars, which have well-defined cycles of activity ("Excellent + Good") and similar color indexes.
- The stars belonging to "Excellent" + "Good" classes are on average characterized by lower level fluxes of the coronal radiation (a median value corresponds to the value of  $\log L_X/L_{Bol} = -5.05$ ), while stars without cycles have higher level fluxes of the coronal radiation (a median value corresponds to the value of  $\log L_X/L_{Bol} = -5.75$ ).
- There is a great interest now to the problem of finding planets of habitable zone which is the region around a star where a planet with sufficient atmospheric pressure can maintain liquid water on its surface. We believe that in search of life on exoplanets the close attention should be paid to the characteristics of our Sun: a low level of variability of the photospheric radiation simultaneously with a very low level of the coronal radiation. So the search for extraterrestrial life should be conducted simultaneously on the "planets of habitable zone" and on the "stars comfortable for the life", such as the Sun.



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